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The interventional magnetic resonance imaging suite: Experience in the design, development, and implementation in a pre-existing radiology space and review of concepts

Azmi, Hooman ; Gibbons, Mary ; DeVito, Michele C ; Schlesinger, Mark ; Kreitner, Jason ; Freguletti, Terri ; Banovic, Joan ; Ferrell, Donald ; Horton, Michael ; Pierce, Sean ; Roth, Patrick

Abstract: Background Intraoperative magnetic resonance imaging (ioMRI) has led to significant advancements in neurosurgery with improved accuracy, assessment of the extent of resection, less invasive surgical alternatives, and real-time confirmation of targeting as well delivery of therapies. The costs associated with developing ioMRI units in the surgical suite have been obstacles to the expansion of their use. More recently, the development of hybrid interventional MRI (iMRI) units has become a viable alternative. The process of designing, developing, and implementing operations for these units requires the careful integration of environmental, technical, and safety elements of both surgical and MR practices. There is a paucity of published literature providing guidance for institutions looking to develop a hybrid iMRI unit, especially with a limited footprint in the radiology department. Methods The experience of designing, developing, and implementing an iMRI in a preexisting space for neurosurgical procedures at a single institution in light of available options and the literature is described. Results The development of the unit was accomplished through the engagement of a multidisciplinary team of stakeholders who utilized existing guidelines and recommendations and their own professional experience to address issues including physical layout, equipment selection, operations planning, infection control, and oversight/review, among others. Conclusion Successful creation of an iMRI program requires multidisciplinary collaboration in integrating surgical and MR practice. The authors' aim is that the experience described in this article will serve as an example for facilities or neurosurgical departments looking to navigate the same process.

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Original Article

The interventional magnetic resonance imaging suite: Experience in the design, development, and implementation in a pre-existing radiology space and review of concepts

Hooman Azmi[1], Mary Gibbons[2], Michele C. DeVito[2], Mark Schlesinger[3], Jason Kreitner[4], Terri Freguletti[5], Joan Banovic[5], Donald Ferrell[4], Michael Horton[2], Sean Pierce[2], Patrick Roth[1]

Departments of [1]Neurosurgery, [2]Radiology, [3]Anesthesiology, [4]Operations, [5]Perioperative Services, Hackensack University Medical Center, Hackensack, New Jersey, United States.

E-mail: *Hooman Azmi - hoomanazmi@gmail.com; Mary Gibbons - mary.gibbons@hackensackmeridian.org; Michele C. DeVito - michele.devito@hackensackmeridian.org; Mark Schlesinger - mark.schlesinger@hackensackmeridian.org; Jason Kreitner - Jason.kreitner@hackensackmeridian.org; Terri Freguletti - terri.freguletti@hackensackmeridian.org; Joan Banovic - joan.banovic@hackensackmeridian.org; Donald Ferrell - donald.ferrell@hackensackmeridian.org; Michael Horton - michael.horton@hackensackmeridian.org; Sean Pierce - sean.pierce@hackensackmeridian.org; Patrick Roth - patrick.roth@hackensackmeridian.org

***Corresponding author:**
Hooman Azmi, MD, FAANS,
680 Kinderkamack Road Suite 300,
Oradell, New Jersey,
United States.

hoomanazmi@gmail.com

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ABSTRACT

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Conclusion: Successful creation of an iMRI program requires multidisciplinary collaboration in integrating surgical and MR practice. The authors' aim is that the experience described in this article will serve as an example for facilities or neurosurgical departments looking to navigate the same process.

Keywords: Interventional magnetic resonance imaging design, Interventional magnetic resonance imaging, Intraoperative magnetic resonance imaging, Magnetic resonance imaging development

INTRODUCTION

Since the development of the first intraoperative magnetic resonance imaging (MRI) (ioMRI) units in the 1980s,[20] ioMRI has allowed for advances in the real-time imaging during

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surgeries,[13] improvement in accuracy and safety of procedures,[3,6,17,20-23,27,29] and offered less invasive alternatives for the treatment of lesions in the brain.[10,18,20,24] The costs associated with the development and buildout of intraoperative units in the surgical suite, as well as the limitations in the recuperation of these costs, have hampered the expansion of this technology in most institutions. More recently, some authors have demonstrated the utility of an interventional hybrid unit based in the radiology suite that overcomes some of these financial obstacles.[15,26] This hybrid surgical/MRI environment, while removing some economic hindrances, presents the team with other potential challenges.

The acuity and complexity inherent in both a surgical environment and MRI space necessitate a careful, comprehensive approach to the hybridization of the two in an interventional MRI (iMRI) suite.[12,13] The vigilant physiologic monitoring and strict observation of infection prevention and control measures required in the surgical realm are not traditional considerations of the MRI domain. Similarly, meticulous adherence to magnet safety issues is not a mainstay of surgical personnel training. Thus, the planning, development, and design of an iMRI suite must be a multidisciplinary endeavor, engaging members from the relevant surgical specialties, radiology, anesthesiology, nursing, hospital engineering, and facilities planning, among others.

Despite a wide number of recommendations and guidelines from accrediting and professional organizations on ioMRI safety and design, there is a relative paucity of published reports describing the experience of planning and developing an iMRI unit and the challenges faced in the process, in particular, when designing this unit to fit into a preexisting space with a limited footprint. To the authors' knowledge, only three such reports, those of Childs and Bruch at Yale-New Haven Hospital, White *et al.* in the UK, and Cherkashin *et al.* in Russia, have been published to date.[4,5,28] As another example of navigating this process, we describe our experience in developing an iMRI suite for, but not limited to, neurosurgical procedures.

METHODS

The integration of operating room specifications and optimal magnet function and safety requirements is complex. At our institution, this process was informed by utilizing a number of key resources, including the American College of Radiology (ACR) guidance document for safe MR Practice, the Association of Perioperative Registered Nurses' "Successful Management of Risk in the Hybrid OR," the magnet manufacturer's recommendations/specifications, and the Facilities Guidelines Institute's Guidelines for Design and Construction of Hospitals.[5,7,8] In addition, the Centers for Medicare and Medicaid Services require observation of infection control practice elements.[11] Compliance with state ordinances for both the design plan and Infection Control Risk Assessment also had to be established and approved by the New Jersey Department of Health. All this had to conform to the limitations implicit in the preexisting floor plan without the luxury of being able to redesign the entire floor.

RESULTS

Suite design

Physical layout

The limitations posed by designing the iMRI unit to conform to the pre-existing floor plan was our biggest challenge.. The existing MRI suite was designed with two imaging rooms with an adjoining control room and other necessary access areas. The redesign of the entire suite was both cost prohibitive and also would have rendered an inpatient magnet inoperable for a period of time, and this was simply not feasible. The best alternative was to reconfigure one of the rooms while staging the build and maintaining the other magnet functional. As such, the design had to incorporate all state requirements for an operating room build within our confined limitations including a secure antechamber, a scrub sink, a recovery area, and a holding area. Moreover, these requirements also had to be designed with strict adherence to MRI safety concerns. Multiple iterations of the design were reviewed, and in the end, what was submitted and ultimately approved is demonstrated in Figure 1.

In general, both ioMRI and iMRI suites can be configured with either mobile or stationary scanners. The former scanner type needing to be transported to and from the operating area, and the latter requiring the patient to moved into and out of the magnet. They each present their own set of challenges for costs, operating space, safety and surgical limitations, and expectations for the ratio of interventional versus diagnostic procedures. The advantages and disadvantages in these general approaches have been well documented in the literature. Table 1 summarizes some of these differences. In short, the capability of moving the magnet into the OR and back out when the imaging is completed presents at least two main advantages. In this design, non-MRI compatible surgical instruments can be used allowing the full breadth of available instruments. Indeed, currently, MRI compatible instruments are quite limited, and this may pose an issue for performing neurosurgical procedures. In addition, the magnet can be moved to the non-surgical adjoining room which allows it to be used for diagnostic scans when it is not needed for surgical cases.

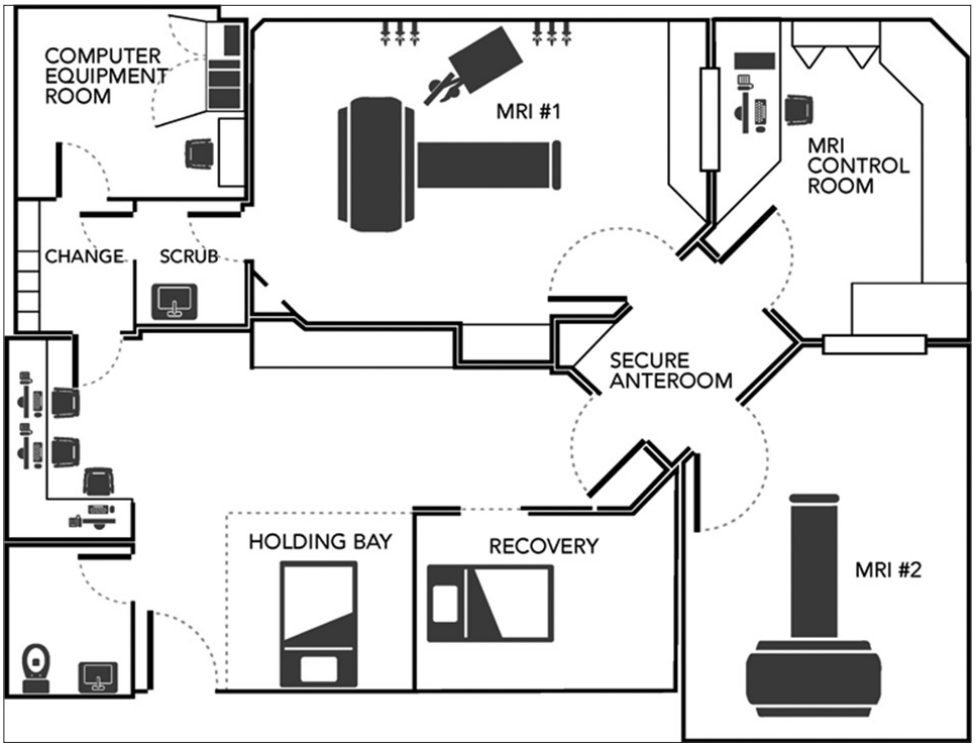

Figure 1: Layout of the magnetic resonance imaging (MRI) suite with the preexisting and new unit. The new unit was placed in the room signified as MRI #1. The anesthesia unit is depicted in the room. The MRI suite was designed to incorporate requirements of a surgical OR in the preexisting footprint.

Table 1: Comparison of mobile and stationary io/iMRI units.

	Mobile	Stationary
Cost of build	+++++	+++
Space requirement	+++++	++
Surgical limitations	++	+++++
Need for MRI safe equipment*	*	*
Patient position	Patient position stable, magnet moves onto patient	Patient position stable/or patient moved from surgical area to MRI for imaging

*In mobile scanners and stationary scanners, where patients are moved into a magnet from another surgically designated space, MRI unsafe surgical equipment may be used but must be removed before moving the magnet or placing the patient into the magnet. For surgical procedures which are conducted in stationary magnets without moving the patient elsewhere for surgery, MRI safe equipment must be used. MRI: Magnetic resonance imaging, io/iMRI: Intraoperative/interventional magnetic resonance imaging

These advantages are offset by certain detractors of this design. As ferromagnetic instruments are used for the surgery, they need to be removed when the magnet is entering the room. The transformation of the operating area to an MRI safe environment requires a high level of vigilance with multiple levels of safety checks prior to magnet entry. The more practical disadvantage, however, is the cost associated with this design. A standing 1.5T MRI scanner costs can range from 1 to 3 million US dollars. The cost of construction alone for the required ceiling rail system to move the multiton magnet into and out of the room is at least 1–2 times the cost of the scanner. This is in addition to the regular costs of an OR build-out.

This expense has limited the use of the mobile magnet to a few centers. The hybrid OR/MRI room has recently evolved to address this obstacle. Institutions interested in acquiring intraoperative MRI capabilities now have the option of building hybrid rooms with standing MRIs in the operating suite. The MRI room is adjacent to the OR, and patients are brought into the magnet room from the OR mid-surgery or at the end of the procedure when imaging is needed. When there is no need for intraoperative imaging, the MRI room can be used for diagnostic scans. While the discussion for these two options is relevant when designing a new building or complete OR suite, these choices were not available to us as we had to design our

unit in a preexisting space within the radiology floorspace. The limitations enumerated at our institution allowed for a stationary second MRI scanner contiguous to the existing MRI suite. While this permitted cost savings in utilizing the existing control room, shielding, and the fringe field accountability, there were challenges in hybridizing the surgical and MRI environment within a space with such immutable parameters [Figure 1].

MRI zones

The ACR defines four critical zones relative to any MRI suite, which are outlined in Table 2. Zone I is essentially any area openly accessible to the general public outside of the MRI environment. Zone II is the interface between Zone I and the tightly monitored Zone III and is where patient histories and MRI screenings are typically performed. Zone III access must be strictly controlled by MR personnel. Unscreened individuals and ferromagnetic equipment represent significant hazards within Zone III due to the potential for interaction with the magnetic field. Zone IV is where the magnet itself is located. Any non-MR personnel who enters Zone IV must be supervised by a Level 2-trained MR staff member. The ACR defines Level 2 personnel as "individuals who have been more extensively trained and educated in the broader aspects of MR safety issues."[7]

Figure 2 demonstrates the layout of the critical zone locations. The control room provides a line of sight view into Zone IV through an observational window which is augmented by video monitors providing live imaging of both Zone IV, including all entrances, and Zone III. The window allows for multiple individuals, including the MRI technologist, neuronavigational platform clinical

Table 2: MRI zones as defined by the ACR.[7]

Zone I	All areas freely accessible without the need for supervision
Zone II	This zone separates Zone I, which is unregulated, and the strictly controlled Zones III and IV. Safety clearances are performed here
Zone III	An area near the magnet room where magnetic fields are sufficiently strong to present a physical hazard to unscreened patients and personnel
Zone IV	The MRI magnet room. This area has the highest field and the highest risk. All ferromagnetic objects must be excluded from this area

MRI: Magnetic resonance imaging, ACR: American College of Radiology

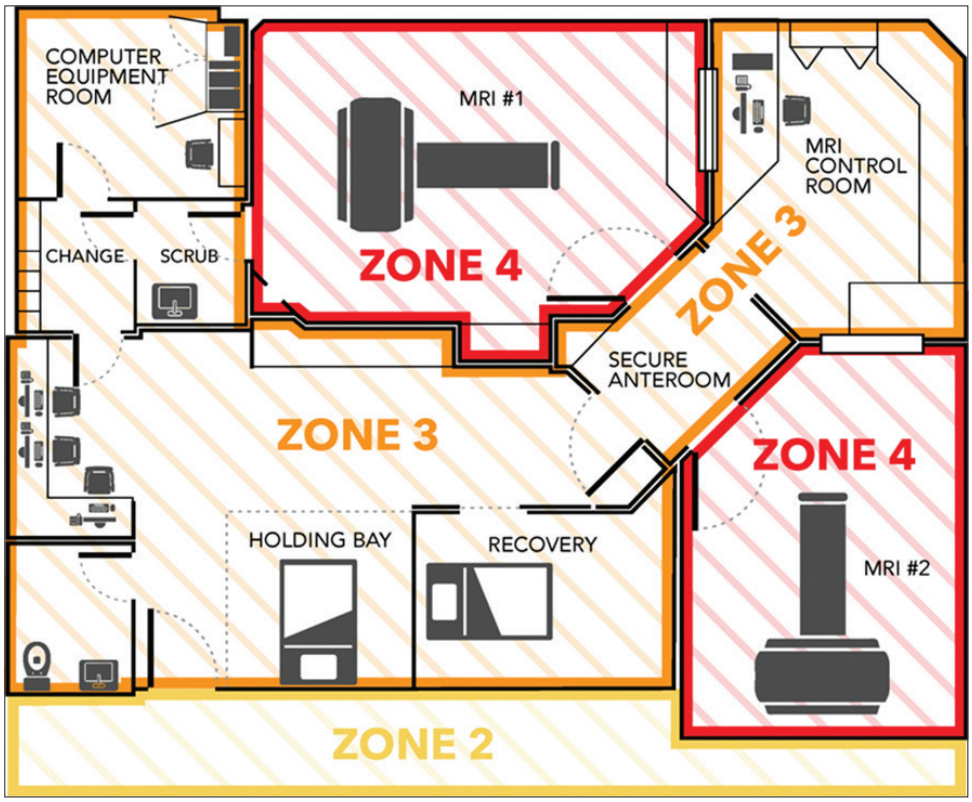

Figure 2: Layout of the magnetic resonance imaging (MRI) suite with outlined MRI zones. Zone IV has two entrances, one from the secure anteroom in Zone III, adjacent to the control room, and another from the surgical scrub room. This direct access configuration minimizes the risk of the staff being contaminated when going through other areas.

specialist, and anesthesiologist, to have visualization into Zone IV [Figure 3].

Static field and radio-frequency (RF) screening

All MRIs must have RF screening provided by a Faraday cage for proper functioning.[25] At our institution, the Faraday cage is created by copper shielding surrounding Zone IV. Copper mesh was used to extend the cage through the window between Zone IV and the control room. Two RF doors provide entrance into the cage. All electrical services into the cage are made through waveguides with all data links made through fiber-optic cables. The waveguide also allows the use of other necessary equipment such as pneumatic compression stockings and bipolar electrocautery where the MRI incompatible devices can be in the control room and the tubing for the compression devices and the cables for the bipolar electrocautery and the pedal run into the control room. The waveguide is positioned in the wall at the opposite end of the room from the patient's head and opens directly into the control room. Cables and tubing are run along the room's borders and secured to limit the chance of tripping or accidental pulling. All electrical services in the suite have a UPS backup in the event of a hospital-wide power failure. The 5-gauss line is a critical area within Zone IV and is demarcated by markings on the floor so that it is visible to all staff in the room.

Air circulation and ventilation

Air curtain systems have been demonstrated to reduce air turbulence near the surgical field and potentially reduce contamination of the field by particulate matter. The iMRI room was designed with current recommendations and guides incorporating an air curtain system.[14] This construction integrates laminar flow diffusers surrounded by vertical air curtains [Figure 4]. The air curtain diffusers provide a higher velocity of air (average of 25–35 cfm/ft^2) than the interiorly placed laminar air diffusers, creating a constant velocity differential between the lower laminar flow and a higher velocity "curtain."[19] Air distribution in this manner is thought to prevent recirculation of contaminated air back into the interior zones. To further reduce contaminants, high-efficiency particulate air filters are used in the diffusers through which the air circulates into the suite. This combination of laminar flow, air curtain and air filters, and properly placed exhausts can reduce the risk of field contamination during surgery.

Equipment decisions

Selection: Magnet and coil

The choice of scanner is arguably the most significant equipment decision in designing an interventional suite as it directly and indirectly will dictate the subsequent

Figure 3: View of the interventional magnetic resonance imaging unit through the control room.

Figure 4: View of the air flow system demonstrating the air curtain outlets surrounding the laminar flow diffusers.

requirements of the design. At our institution, a 1.5T cylindrical bore diagnostic scanner (Magnetom AERA, Siemens, Erlangen, Germany) was chosen with a wide bore (70 cm). This decision was based on our prior experience with Siemens, bore size availability, familiarity of MR staff with the hardware and software, compatibility of the units with the existing IT setup, and the engineering of patient movements into and out of the scanner on the MRI bed.

The receiver coil used at our institution is a 4-channel flexible wrap-around coil that is iPAT-compatible (Flex Large 4, Siemens, Erlangen, Germany).

Selection: Surgical and anesthetic equipment

Our equipment selection was informed by the American Society for Testing and Materials (ASTM) designation for

MRI equipment. ASTM categorizes MRI equipment safety. MRI safe designated equipment can be safely used within the 5-gauss line. MRI conditional equipment can be used within the 5-gauss line with certain parameters and MRI unsafe equipment should not be used in Zone IV.[2] In addition to the obvious need for an MR compatible system, the footprint and maneuverability of the anesthesia unit are important elements, given the limited space within Zone IV and particularly around the patient's head. The unit chosen at our institution is certified to field strengths up to 40 mT/400 Gauss and is capable of providing ventilation for both 1.5 and 3T scanners. Ventilation is provided by a piston system that does not require drive gas. The anesthesia unit's breathing system can be mounted on either side of the cart to accommodate the suite's layout and is positioned on a short, flexible arm allowing for easy maneuverability within the perioperative space. The room had to be designed with supplies of oxygen, nitrogen, air, and suction. Both inhalation and intravenous anesthesia can be provided with the MRI compatible pumps. Induction is completed in the MRI suite (Zone IV) or in Zone III if a difficult airway is anticipated.

For our instruments, a standard neurosurgical MRI-safe instrument tray was created to include all instruments potentially needed in any procedure and was tested and approved by the MR Safety Officer (MRSO) before use in the iMRI. An MRI-safe titanium surgical drill (Aria Drill systems, Stryker, Kalamazoo, MI) was also purchased to be available for these procedures [Figure 5]. Other MR equipment are listed in Table 3.

Table 3: List of MR safe equipment utilized in iMRI procedures.

Anesthesia machine	Draeger, Telford, PA
Infusion pump	i-Radimed, Winter Springs, FL
Syringe driver	MedRAd, Whippany, NJ
Anesthesia monitor	INVIVO, Gainesville, FL
Surgical instruments	Stealth Surgical, Gordonsville, VA
Pneumatic drill	Stryker, Kalamazoo, MI
Pneumatic compression device*	Covidien, Minneapolis, MN

*Only the leg stockings are MRI safe. The pneumatic machine is kept in Zone III with the tubing running through the waveguide. MRI: Magnetic resonance imaging, iMRI: Interventional magnetic resonance imaging

Figure 5: Image demonstrating magnetic resonance imaging safe equipment including a pneumatic drill.

Selection: Lighting

Lighting is obviously an important element in optimizing the surgical staff's visualization of both the surgical site and surgical equipment. In the iMRI suite, light-emitting diode sources were selected as they have been shown to reduce noise or image artifact.[22]

Operation planning

Access control

Access control is a critical issue in any MRI suite; however, it becomes even more important in an iMRI unit in which the presence of surgical personnel entering and exiting the suite adds to the overall volume of foot traffic and air turbulence. Entrance from Zone II into the secure anteroom (Zone III) is through a locked door which requires a security ID swipe, issued only to MRI staff, for opening. The only staff who are permitted unsupervised access into Zones III and IV are level 2 trained personnel. Level 2 certification requires completion of advanced MRI safety training. All Level 1 personnel, including anesthesiology and surgical staff, must be accompanied by Level 2 personnel and must defer to Level 2 while in Zone III or IV.

Safety training

A detailed description of the cross-training of both MR and surgical personnel is beyond the scope of this article, and the essential elements required have been previously outlined by Larson *et al.*[16,17] This cross-training is critical for any iMRI program and represented one of the biggest challenges in the early phases of the iMRI program at our institution.

All staff with access to the iMRI suite must undergo an MRI safety class with the MRSO. Ongoing competency is ensured by an annual refresher course and examination. The head of MRI technology serves as the procedure safety officer and is present for every surgical procedure, while the head clinical radiology nurse serves as the circulating nurse for each procedure.

All surgeons undergo MRI safety education supervised by the MRSO in addition to being proctored for their initial surgeries by the primary neurosurgeon.

Staff responsibilities and workflow

A patient's journey for an interventional procedure begins in the Radiology Day Accommodation Room, which is in Zone I. Before transport of the patient to Zone IV, the patient is seen by the surgical and anesthesia teams and on completion of safety checklists.

Safety checklists have long been proven to be a highly effective means of providing this monitoring for both MRI and surgical procedures and have become a standard of care.[7,30] At our institution, there are three checklists performed for each patient. A limited MRI safety questionnaire is performed over the phone before admission. On the day of the procedure, a comprehensive six-phase MRI/surgical checklist, as shown in Table 4, is completed. This checklist has evolved since the first procedures were performed in the iMRI unit and represent a culmination of the experience of the staff and departments involved in iMRI patient care.

Infection control

Perhaps, one of the most challenging and yet critical issues related to the hybridization of the OR and MRI is that of infection prevention and control of the MRI environment. There are no formal recommendations from any professional or accrediting organization regarding cleaning protocol for an intraoperative MRI suite. The ACR guidance document on MR safe practice addresses the fact that the design of the suite should facilitate easy cleaning (e.g., surfaces that can be scrubbed, seamless flooring). It further states that cleaning staff that enters Zones III and IV must either be Level 2-trained or supervised by Level 2 staff in those areas,

Table 4: MRI surgical checklists and briefing/de-briefing forms

MRI-Surgical Holding Area	**Zone III**
MRI TIme-Out Safety Checklist	Completed by MRI tech
Consent #2	Signed and/or confirm in chart
Patient seen by Surgeon	
Patient seen and Evaluated by Anesthesiologist	
Head Shaved	
All staff/vendors in appropriate hospital surgical attire	Scrubs/Hats/Gowns/Mask/Shoe covers
All staff have removed ALL personal items	
MRI Surgical Preprocedure Checklist	
Check off each item below	
Pre-Op	
Admission completed	Admit Consent Form signed
At Home Meds in Original bottle	with time schedule
Identification Bracelet on patient	
Patient chart together	
H & P	
Bloodwork	CBC/SMA7/PT/PTT/INR
EKG	
UA	
CXR	
HgbA1C	
All relevant clearances	Cardiology/Pulmonology/GFR
2 Peripheral IV Hep-locks	
MRI order	Brain with contrast
Transfer level of care order entered	
Patient belongings in garment bag	to accompany patient

PRE Procedure Room Walk-through: Prior to Patient Entering Scan Room		
Date:	Patient Name:	Med Rec #:
Time:	Procedure:	
	Surgeon:	Anesth:
	Scrub RN:	Cirrculating RN:
		MRI tech:
	Terminal clean completed	Environmental log book signed
	Anesthesia machine terminal clean completed	Anesth tech set up machine for use
	Procedure supply cart stocked and placed in scan room	
	Surgical implants/disposables checked and labeled	Right Left leads and frames marked placed on room supply cart
	Anesth medication tray in room	
	Pyxis stocked with appropriate drugs	
	Clean (2) sharps container/garbage cans in scan room	2 sharps containers 2 garbage cans
	Scrub sink has been cleaned	
	Bipolar machine set up and functioning	through waveguide
	Venodynes setup and functioning	through waveguide
	Floor on sterile side is draped	
	Patient monitor functioning	ECG/Pulse OX/BP/Temp
	Drill set up functioning	Oil/Filter
	Sterile surgical trays checked for ONLY MR instruments	
	Door to Ante-room closed	
	Door to scan room closed	
	MRI table prepped; Frame locked onto table/coil wrapped	
	MRI scout image	
	Confirm scanner and Clearpoint computer communicate	
	Table gantry buttons protected	
	Table docked and in "home" position	
	ClearPoint and Siemens Network communicating	
	Siemens test Scout completed	
	Code Cart outside MRI door	

MRI Surgical Briefing	
Check off each item below	
MRI Surgical Suite-ZONE IV	Scan room
ET Tube in place with Straight connector and condensation filter in place	
Full Patient Monitoring/Vitals functioning	
Stockings in place	
Pneumatic compression boots functioning	
Foley Catheter in place	
Temp Probe in place	

Pillow placed under b/l knees		
Elbow/Wrist/Sacral Pads in place		
Heel pads in place		
Complete Final TIME_OUT		with entire surgical team in attendance
Circulating Nurse's dialog:		To be done in Scan Room ZONE IV with patient in position
This is Mr./Ms	here today for _____ under MRI guidance with Dr.	
The patient's allergies are	.	
Team members are :		
Anesthesiologist		
Scrub nurse		
Circulating nurse		
MRI Safety Officer		
Technologist scanning		
Antibiotics admin time	to be repeated _____.	Blood Pressure requirements _____
PRE Procedure BRIEFING completed _____ .		All implants are in the room, Yes/No.
Questions/unresolved issues?	Is EVERYONE in agreement?	
MRI Surgical De-Briefing		
Post OP diagnosis		
Procedure Performed		
Counts Correct		Instruments/Laps/Sponges/Sharps
All Instruments/Equipment/Implants were available		
Any Improvements for flow of case?		
PACU/Post OP Considerations		Pain management/Isolation/Labs
Additional Concerns?		
Nurse Completing this Form:		Date/Time:

in addition to being thoroughly screened before entry into them.[7] As such, all environmental services (EVS) staff undergo MRI safety training sessions, on hiring and annually. In addition, a Level 2 MRI technologist performs safety screening of all EVS personnel before their entrance into Zone IV and remains present to supervise.

Emergencies

Emergencies in the iMRI can be broadly categorized into those that are primarily related to the patient and those that are primarily related to the magnet. Before initial use of the iMRI, a protocol for a cardiopulmonary emergency code had already been established. The protocol conforms to that recommended by the American Society of Anesthesiologists Task Force on Anesthetic Care for MRI.[1] Should a cardiopulmonary emergency code occur in Zone IV, the patient is immediately moved from Zone IV to the MRI holding area in Zone III, and cardiopulmonary resuscitation initiated. The MRI scan room door is locked once the patient and staff exit scan room and the code cart is brought into Zone III from its storage location in Zone II. MRI staff is directed to stand at the security door to assist and monitor the code team.

The most significant magnet-related emergency that can occur in an MRI is a quenching, in which the magnetic coils rapidly lose their absolute zero temperature leading

to the elimination of the magnetic field. Helium escapes from the magnet's cryogen bath when this occurs, and a venting system is required to direct the helium out of the suite to avoid atmospheric oxygen depletion and increased pressurization in Zone IV.[7,22] At our institution, an emergency "quench" shutdown can be initiated by a Level 2-trained MRI personnel, with shutdown buttons located in Zone III or IV. When a quench is initiated, the quench valve opens and helium pressure breaks the BURST valve and is expelled through the quench pipe to the atmosphere outside the building. There is additionally a secondary backup or auxiliary pathway for the helium to exit the building.

Oversight/review

A critical aspect of the ongoing success of an iMRI is the continued review of practice and protocol by all stakeholders.[12] At our institution, this occurs through two means: regular meetings of the Quality Control Council for Neurosurgery and informal but frequent communication between the team members represented in the original multidisciplinary planning committee.

The current checklist and briefing tool have been developed and expanded over the course of the past 5 years by incorporating the lessons learned at our institution, utilizing and modifying the currently available tools, and the consensus developed as a group to anticipate potential safety issues, in a best attempt to avoid these lapses. Fortunately, there has been no compromise of the safety of patients during these interventional procedures, and nearly 100 of which have been performed to date, suggesting that the safety protocol has served well. Nevertheless, the protocol continues to be assessed and reevaluated to ensure any gaps if remaining are addressed.

DISCUSSION

In their 2000 review, intraoperative magnetic resonance imaging and interventional magnetic resonance imaging: recommendations for A Safe Environment, Kettenbach *et al.* advised that there should be "a gradual progression in establishing an iMRI suite. The right team members, well thought-out architectural planning, and proper policy and training are an essential start. Human vigilance and enforcement of policy must be ongoing. For any new procedure, a dry run should be executed to identify pitfalls. A small core staff should be involved in the first cases… in expanding the services, the experienced core staff should train new staff members."[13] This model proved to be a successful one for our institution. The early cases in a retrofitted MRI suite helped identify needs for the iMRI unit and, along with the subsequent cases, informed the evolution of the workflow and comprehensive checklists used for each procedure. The surgical cross-training of a core radiology staff for each procedure helped to ensure consistency and fidelity to magnet and surgical safety protocol. Incorporation of new staff members has been systematic and their training regimented.

Integrating all of these elements, from architectural planning to staff cross-training, to achieve a fully functional ioMRI unit obviously requires considerable capital outlay and resource expenditure. This funding is often a significant barrier to a facility's development of an ioMRI program. A seminal study by Hall *et al.*[9] demonstrated that the potential for a return on investment with ioMRI in neurosurgery is significant. In a retrospective analysis, they compared costs and clinical outcomes for brain tumor resections over a 5-year period performed in ioMRI compared with conventional ORs.[9] Among adults who had tumor resection performed in an ioMRI compared with conventional OR, there was a 54.9% shorter hospital length of stay.[9] Among adults with first tumor resection and repeat resection (RR), total hospital charges were 14.4 and 3.3% lower, respectively, for those whose procedures were performed in an ioMRI compared with an OR.[9] Furthermore, there were no RRs for those patients whose procedures were performed in an ioMRI while 20% of patients whose procedures were performed in the conventional OR had RRs, suggesting an enhanced ability to achieve complete tumor resection.[9]

While such an analysis has not yet been performed at our institution, the realized benefits of having an iMRI, both for patients and the hospital, have been multifold. There has been a significant expansion of services in the neurosurgical department, including the ability to perform deep brain stimulation procedures with MRI guidance, laser ablation for tumors and medication-resistant epilepsy, minimally invasive brain biopsy for deep-seated tumors, and MR-guided direct drug delivery. Access to a separate iMRI has allowed for increased patient throughput in the conventional MRI suite which is consistently in high demand at our institution. In addition, other surgical specialties may begin utilizing the iMRI unit for other procedures such as prostate and breast biopsies, helping to maximize utilization and further achieve a return on investment.

CONCLUSION

As MRI guidance technology continues to play a more significant role in surgical procedures, the need to hybridize the MR and surgical environment will increasingly become an issue for health-care facilities. Institutions will need to assess their surgical needs, along with their financial and physical limitations, to determine what scanning configuration (i.e., use of a mobile scanner brought into the OR or a stationary scanner in a dedicated unit) best suits them. Careful consideration of the differences among

these configurations in light of an institution's needs and limitations can inform their design decision. Ongoing multidisciplinary collaboration in the development and subsequent implementation of that design, in addition to reliance on available guidelines, recommendations, and other facilities' experiences, can result in a highly efficient and safe hybridized MR/OR environment.

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Conflicts of interest

The corresponding author has a consulting agreement with Medtronic Inc and Abbott Scientific. All of the other authors certify that they have no conflicts of interest.

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